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Abstract

This paper examines the potential use of using submillimeter wave technology (actually 3 mm to 100 μm, or frequencies between 100 GHz and 3 THz) for SDI applications, especially for endo-KEW systems. We start with the requirements and functions for a multipurpose weapon sensor. Our emphasis is on active sensors, but certain elements of passive sensors are mentioned that could play an important role. The rest of the paper provides information on the state-of-the art in submillimeter wave technology, especially current component activity, and future plans.

1. Requirements and Functions

An endo-KEW sensor ideally will perform many functions. For example, the Brilliant Pebbles concept used the same sensor for both ranging/surveillance and communication. At the same time, the sensor and weapon have stringent size, weight, and cost requirements. The submillimeter wave regime provides an ideal middle ground with the advantages of both the IR and microwave portions of the spectrum, especially for active sensors and communication systems. These advantages include: 1) shorter wavelength than microwaves for improved Doppler and angular resolution, 2) use of phased-array antenna techniques, 3) increased bandwidth over current technology for improved range resolution, 4) exploitation of atmospheric transmission windows, and 5) potential for passive sensing capability of molecular emission from rocket plumes or other sources. This section defines and illustrates some of these advantages along with the requirements of a submillimeter wave system.

The short wavelength of the submillimeter wave region compared to micro- and millimeter-waves provides improved Doppler and angular resolution. Doppler resolution (Δx) is a direct function of wavelength (λ):

$$\Delta x = \frac{\lambda}{2\Delta\theta},$$

where $\Delta\theta$ is the aspect angle change through which the target moves for coherent processing. For the same $\Delta\theta$, a wavelength of 0.5 mm (600 GHz) provides 6 times better resolution than 3 mm (100 GHz), 60 times better than 3 cm (10 GHz, X-band).

Similarly, angular resolution is a direct function of wavelength given constant aperture size. In practical use, however, it may be more suitable to maintain the same wavelength and aperture ratio across a wide range of frequencies. This maintains the same gain and beamwidth at the sacrifice of collection area. It also means that more antenna elements can be placed in a structure of a given size. These elements can be combined into a phased array system, and an overall improvement in gain can be realized from the increased number of elements. This is important because as we will see, current submillimeter wave transmitter components are extremely low power. Hence, a straightforward way to make up power is to add individual transmitter/antenna elements.

Phased array systems have other advantages for both sensor and communication systems. Rapid beam steering means fast revisiting and tracking of multiple targets. The phased array also allows

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adaptive nulling of interfering sources such as jammers.

To examine this more closely, let us assemble a submillimeter wave phased array system. Assume a gain, G, of 40 dB for an antenna at 20 GHz. For higher frequencies, we will take the ratio of the antenna areas based on the squares of the wavelengths to determine the number of elements, n, that can be placed in the same physical area as the 20 GHz antenna. Now assume a system temperature, T, in Kelvin numerically equivalent to the center frequency (in GHz) divided by 2. If we allow a 13 dB "rule of thumb" signal-to-noise ratio (S/N) to account for such items as system losses, probability of detection, and false alarm rate, we can compute the power needed for single-hit detection of a target with a cross-section, σ, of 0 dBsm using the radar equation:

$$Power = \frac{(4\pi)^3 (S/N) kTBR^4}{\sigma (nG)^2 \lambda^2},$$

where B = pulse bandwidth, R = range to target, k = Boltzmann's constant, and λ = wavelength.

Table 1 presents how many watts per element as a function of frequency and range to target. The power per element actually drops as frequency increases because the number of elements in a given area increases.

Table 1. Power (watts) per antenna element as a function of frequency and range.

Freq. (GHz)	# of elem.	10 km range	50 km range	100 km range
20	1	14.6	9110	146000
100	25	0.116	72.8	1170
500	623	9.42e-4	0.588	9.42
1000	2516	1.14e-4	0.714	1.14

The data presented in Table 1 represent a rough order of magnitude for estimation purposes. In reality, system noise temperatures, target cross-sections, and other parameters will vary and affect the system. However, for typical working ranges of an endo-KEW sensor, it is obvious that power requirements of less than a few watts per element are necessary. Since required communications power is a function of range squared, not range to the fourth power as in radar, the power per element in Table 1 will easily accommodate communication needs.

This regime has the capacity of larger bandwidths, as will be seen later in the technology section. Current microwave technology allows up to 2 GHz bandwidths in practice, submillimeter wave promises up to 10 GHz or greater bandwidth. Allowing for window weighting, this means an improvement from about 15 cm slant range resolution with 2 GHz bandwidth to about 3 cm resolution with 10 GHz bandwidth.

Wider bandwidths provide other benefits. Higher data rates are possible for communication. Spread spectrum techniques can take advantage of the enhanced frequency agility for advanced jammer rejection and other ECCM capability.

Transmission at submillimeter wavelengths has a strong dependence on frequency due to strong atmospheric molecular absorption. This "disadvantage" does have a potential "advantage" in that these atmospheric windows can be exploited to allow for both covert space-to-space and open space-to-ground communication. An example is the narrow CO absorption band at 120 GHz, on either side of this frequency the atmosphere is relatively transparent. A wide bandwidth device could conceivably provide full communications capability for an endo-KEW or other system.

Another possible way to make use of the submillimeter molecular lines is to search for emission lines from rocket plumes or absorption lines from surface materials. The submillimeter wave frequencies are especially rich in rotational and vibrational molecular lines. Further research is necessary to identify molecular line candidates and possible "clutter frequencies" in the submillimeter wave band. To use the submillimeter wavelengths for passive sensing it would also be useful to map out the corresponding celestial background.

2. Current Submillimeter Wave Technology

As discussed above, there are several important SDI applications for a submillimeter wave system. The sensor of choice for these

applications is a heterodyne receiver due to its high sensitivity and spectral-resolving power. Basically, a heterodyne receiver takes a weak, incoming, high-frequency (submillimeter wave) signal and mixes it in a nonlinear device with a local oscillator (LO) signal to produce an intermediate frequency (1-10 GHz) signal which can be analyzed. The principle components are an antenna (or antenna array) to receive the incoming signal, a diplexer to couple in the local oscillator, an SIS tunnel junction to serve as the nonlinear mixer, an r-f embedding circuit to optimize the mixer, an intermediate frequency amplifier, and a high-speed signal processor to analyze the signal. In addition, if the receiver is used in a radar or communications system, a high-power transmitter source is needed. Most of the r-f components in the transmitter are similar to those in the receiver, except that the oscillator source must produce a large amount of power. The status of these components is briefly reviewed.

Most of the work reviewed here will center around that carried out through the Terahertz Technology Program, Rome Air Development Center for the Strategic Defense Initiative Organization Innovative Science and Technology Program (SDIO/IST), and that work done at the Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, for SDIO/IST through NASA.

The nonlinear quasiparticle tunneling characteristics of a superconductor-insulator-superconductor (SIS) tunnel junction are well suited for low-noise heterodyne mixing. This has led to the rapid development of SIS mixers for use in low-noise millimeter wave receivers for radio astronomy. The performance of these devices surpasses that of competing technologies[1-8]. A quantum theory of mixing, proposed by Tucker[9], predicts that the available mixer conversion gain can exceed unity, and the mixer noise temperature can approach the fundamental noise limit, $T_m = hf/k$, where h is Planck's constant; f is the frequency; and k is Boltzmann's constant[10]. This optimum performance is achieved with an absorbed LO power level typically less than a microwatt. To obtain these useful properties, SIS junctions with high current density, low subgap current, and sharp nonlinearity are required. In addition, the voltage width, ΔV_G, of the nonlinearity should be less than hf/e for the frequency of interest. For the embedding circuit, it is necessary to provide the proper r-f source impedances.

To fully optimize an SIS mixer for lowest noise and broadest bandwidth, a proper embedding network must be provided. The most extensive work to date at millimeter wavelengths has been with waveguide systems. These are well-known structures. They have adjustable tuning elements which compensate for small uncertainties in the mount design and relax some of the junction requirements. Waveguide components and systems have been built for operation to about 700 GHz[11-13]. In particular, JPL has built and tested a waveguide SIS mixer which gave a mixer noise temperature $T_m = 60$ K[7] at 205 GHz. This is the best noise performance reported near 200 GHz. Currently JPL is building a 630 GHz SIS receiver[13] for astrophysical remote-sensing applications. Preliminary measurements show its noise temperature to be a factor of 2-3 lower than competing technologies. A further improvement of about a factor 3 is expected as the mixer is developed and optimized.

Operation of waveguide to 1000 GHz is also possible. Such small waveguides become difficult but not impossible to fabricate. Micromachining of silicon should also extend performance to well above 1000 GHz[14]. Losses increase with frequency; however, the loss per wavelength is usually tolerable. Mixer blocks can be designed with 5 to 10 wavelengths of waveguide, so losses are not a serious problem. In fact, waveguide is the lowest loss transmission line available. Waveguide systems can be designed with bandwidths of 20% which would meet many instrument requirements. This would give 200 GHz of bandwidth at 1 THz! The ultimate limit on bandwidth, however, is determined by the ωRC of the junction (where ω is the signal frequency; R, the junction resistance; and C, the junction capacitance). Thus, $\omega RC < 10$ is needed to meet r-f bandwidth requirements of 10%. Raisanen *et al.*[15] and Pan *et al.*[3] have obtained excellent performance near 100 GHz using integrated tuning elements to extend the bandwidth of waveguide mixers to 15% - 30%.

Planar antenna structures have also been used as embedding circuits. Log-periodic, broadside radiating elements have very broad bandwidths,

are easily fabricated with the tunnel junction, and can easily be scaled for operation at 1 THz. In addition, planar antennas can be readily fabricated into large area arrays. As previously discussed, electronically-steered arrays are one of the key advantages of this technology. JPL is developing planar arrays for submillimeter wave operation using a novel optical coupling scheme: a dielectrically-filled parabola[16]. This approach has several advantages. The beam pattern for off-axis pixels is excellent. Planar arrays of 10 x 10 elements are possible with a parabola which is only 40 wavelengths in diameter (this is less than 1 inch at 1 THz). This system has recently given very good performance as a heterodyne front-end at 230 GHz[6].

It should also be noted that any mixer embedding circuit, whether waveguide or planar antenna, will also employ integrated superconducting r-f tuning elements to tune-out the large junction capacitance. These elements are expected to work well up to the superconducting energy gap frequency, f_g. Above this frequency, loss and dispersion will deteriorate the performance[17]. For three of the most useful superconducting materials, lead (Pb), niobium (Nb), and niobium nitride (NbN), the gap frequencies are 655 GHz, 730 GHz, and 1200 GHz, respectively. The SIS mixer performance is also expected to decrease above f_g, though it is expected to operate up to about $2f_g$[18].

High-quality SIS tunnel junctions are required for best mixer performance. The junctions must have a high energy gap voltage for high-frequency operation, a sharp nonlinearity, low subgap current, a suitable r-f resistance (between 20 Ω and 200 Ω), and small parasitic capacitance. In addition, for practical applications, a rugged refractory material such as Nb or NbN is required. Several groups are developing Nb-AlO_x-Nb junctions using a trilayer process. However, the fabrication group at JPL has produced some of the smallest area, highest quality Nb junctions to date[19]. In addition, this group leads the effort to develop NbN-MgO-NbN junctions[20]. Both types of junctions are currently being tested at several frequencies up to around 600 GHz and have given excellent mixer performance. NbN with the higher gap frequency, f_g = 1200 GHz, is the best choice for use at frequencies approaching 1 THz. However, further work on new tunneling barrier materials may be required for these frequencies.

One of the primary types of LO sources currently used to pump SIS mixers at frequencies above 200 GHz, is a Gunn oscillator operating near 100 GHz driving a frequency multiplier. The frequency multiplier usually consists of a whisker-contacted Schottky diode in a waveguide mount. This type of LO is being used in conjunction with the JPL 630 GHz SIS receiver project. The LO, produced by Radiometer Physics[12], consists of a 104 GHz Gunn oscillator followed by x2 and x3 frequency multipliers. It produces at least 200 μW over the 622 GHz to 638 GHz frequency range. These LO sources are lightweight and compact. And while whisker-contacted Schottky diodes have been spaced-qualified for NASA missions, development work is currently underway at JPL and the University of Virginia to produce a planar, whiskerless Schottky which is very rugged and easily integrates with planar circuits. However, to achieve sufficient power levels at 1 THz, additional work is needed on reducing device parasitics and improving the r-f embedding circuit.

Besides conventional Schottky diodes, new layered heterostructure devices, such as quantum-well diodes and single-barrier varactors[21-22], show great promise as high-efficiency frequency multipliers. JPL is currently working with MIT Lincoln Laboratory on these devices. Substantial progress in the theory of these new devices has recently been made[23]. Tests at 205 GHz show the multiplication efficiency of these new devices to be ~6%[22]. Heterostructure devices have unique advantage for submillimeter wave operation since the device properties such as capacitance-voltage and current-voltage characteristics can be uniquely "engineered" during fabrication using advanced MBE technology.

For active applications such as radar and communications, a transmitter is needed that is powerful in comparison with the LO sources discussed above. Communications systems would typically require power levels on the order of a watt or above. Radar systems would require tens to thousands of watts for ranges of thousands of kilometers. Missile homing systems would benefit from submillimeter wave

radar. For these systems, only submillimeter wave radar could produce an electronically-steered beam given the small size of most missiles.

While such power levels have not been generated to date, JPL and others are currently working on different concepts that could provide power at these levels in the future. Two-dimensional arrays of Josephson junctions could provide sufficient power for some of the less stressing communications needs. More importantly, a number of approaches are being pursued for generating higher power levels by arraying semiconductor-based devices. Diodes and/or transistors can be used for generating millimeter waves, with the transistor approach probably being better for reliable phase-locking and for their ease of use with respect to various control functions. The output of these devices can be frequency multiplied by the use of quantum well, Schottky, or heterostructure varactor diodes. Devices can be configured in conventional phased arrays or as grid-arrays; the latter approach could result in watts of power from very small numbers of parts, leading to better system ruggedness and dramatically lower weight and cost.

Conventional phased arrays are currently being developed for millimeter wave frequencies. Such arrays are typically constructed by layering modules, each of which has one or more radiating elements driven by a combination of a source (either an optical or R-F signal from a central feed for all elements), phase-shifter, amplifying stages, and power stages. It is certainly possible that current approaches would work at frequencies over 300 GHz with the addition of one or more multiplying elements on the output of each power device. Such an array could supply an arbitrary amount of power simply by adding more modules, but it would also be quite complicated.

A number of groups have been working on the development of quasi-optical arrays (commonly called grid-arrays) of devices for the generation of microwave and millimeter wave power generation, leading to the possibility of feeding a multiplier grid[24]. These arrays can best be described as being analogous to a laser, although the instability of the electronic devices drives the grid-array in place of the quasi-stable atomic states in a laser. The most common approach has been to combine a number of diodes or transistors in a mirrored cavity, much like a laser cavity, with the unstable devices operating in a single polarization. Similar grids have also been used to produce beam-steering and other functions that would be needed for an actual transmitter. This concept is also compatible with various methods of harmonic generation.

To date, diode grid oscillators have been produced for millimeter wave generation[25], while oscillators using MESFETs or diodes have been made for microwave generation. A collaboration between JPL and Caltech[26,27] has produced a grid-array of transistors that can behave either as an oscillator or a transmitting amplifier. While the test case was an array of discrete transistors, a monolithic version of this array using HEMTs or HBTs could produce watts of power from a single chip at up to 100 GHz or higher. This new design is much more flexible from a system point of view. The array should preserve the phase of an incoming signal, and series of them could be cascaded to form an amplifying chain.

All of the grid-array oscillator and oscillator/amplifier concepts described above, other than Josephson junctions, are probably limited to frequencies below 100 to 200 GHz implying that their outputs must be multiplied. A particularly simple concept for low levels of multiplication is to use a dichroic plate for the output mirror. Such a mirror would reflect the fundamental back to the device but transmit the desired harmonic.

Backend Signal Processing

The wide bandwidth afforded by operating at submillimeter wavelengths requires the development of a new generation of signal processors possessing capabilities well beyond that available today. A bandwidth of 10 GHz is modest for a radar or communication system operating at 300 GHz or higher, but the required signal processing capability is beyond the present state-of-the-art of today's semiconductor technology.

In emerging SDIO applications, such as pulse-compression radar, spread-spectrum communications, and electronic warfare, real-time signal processing is stressed. The required

computational rate is of the order of 10^{12} arithmetic operations per second and the required instantaneous bandwidth approaches 10 GHz. These exceed by nearly three orders of the magnitude the capabilities projected for semiconductor digital systems in the near future and exceed that of recently developed analog technologies such as surface-acoustic wave signal processing devices.

The results of the recent SDIO-sponsored summer studies: The Midcourse and Terminal Tier Review (MATTR) and Global Protection Against Limited Strikes (GPALS) probably have not changed these requirements. Although the size of the threat has decreased, real-time signal processing is still required to neutralize it. Even such crude terrorist weapons as the Iraqi Scud would have resulted in less damage had the Patriot been equipped with an imaging radar in order to direct it only against the warhead and not against Scud debris resulting from its breakup in flight.

The Terahertz Technology Program is pursuing both analog and digital techniques to handle these computational intensive operation requirements for real-time applications. Analog techniques allow processing tasks to be accomplished in real time that would require a computer the size of a Cray, if processed digitally. Also, ultra high-speed superconducting A/D converters and shifter registers are being developed to capture high-frequency waveforms (> 1 GHz) and slow down the data stream to where it can be processed in a parallel format by semiconductor superconducting digital processors.

<u>Analog Signal Processors</u>

Superconducting analog signal processors exploit two properties unique to superconducting thin films: low R-F surface resistance and skin depth that is independent of frequency. This allows long, dispersionless, superconducting delay lines to be built and employed in sensor circuits that would not be possible using normal metal delay lines. These superconducting circuits permit larger time-bandwidth wave forms to be processed than would be possible with competing technologies.

MIT/Lincoln Laboratory is the originator of analog signal processing technology employing superconducting delay lines. This effort evolved from their past development of Surface Acoustic Wave (SAW) delay lines which found many applications in DoD systems. Prior to being supported by the Terahertz Technology Program to develop a superconducting time-integrating correlator, Lincoln pioneered both fixed and programmable superconducting matched filters for pulse compression or expansion.

A 14-cell time-integrating correlator has been fabricated in Niobium and tested at Lincoln. At the current status of the technology the bandwidth is 2.5 GHz and the time bandwidth product is 7500. The operating power is 0.5 mW, 0.5 W including cryocooler power. For comparison, a narrow bandwidth (500 MHz) acoustical optical correlator developed elsewhere requires 5 W operational power. This is ten times the power consumed by the superconducting correlator. Also, whereas acoustical optical technology is mature and appears to be approaching a bandwidth limitation somewhat in excess of 1 GHz, superconducting technology is in a nascent state of development. It should be possible to develop superconducting devices with bandwidth in excess of 10 GHz.

<u>Digital Signal Processors</u>

In addition to low loss, dispersion-free transmission lines, digital superconducting circuits take advantage of the high intrinsic switching speed of Josephson junctions (JJ's). This is 0.22 ps for a niobium junction. The record measured switching speed for a niobium circuit is 1.5 ps, about an order of magnitude slower than the intrinsic limit. The slower speed is a result of parasitic elements such as the resistances and capacitances of the junctions and will be reduced as junction technology improves.

JJ switching speeds exceed that of all semiconductor devices. In addition, JJ's consume less power. This is shown in Figure 1. The gate aperture time/power products are plotted for superconducting and various semiconductor circuits as of 1988. The superconducting circuit gate times are faster than all semiconductor gates, although not always by an order of magnitude. On the other hand, the switching power is always two orders of

magnitude less. In order to take advantage of very fast switching, it is necessary to make extremely dense circuits. The low power consumption of JJ circuits make the required dense packing possible.

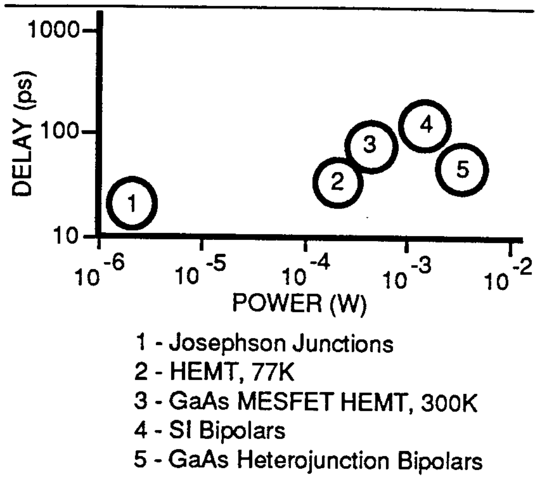

Figure 1. Comparison of gate delay--power characteristics for several digital technologies.

At the time of the formulation of the Terahertz Technology Program in 1986, very little effort was underway to develop superconducting digital circuits in the US. This was primarily the result of IBM's decision in 1982 to cancel its development of a superconducting computer. Programs existed at NIST (formerly NBS) in Boulder, CO, at TRW in Los Angeles, CA and at the University of California at Berkeley.

SDIO has had a major hand in increasing the level of activity in superconducting electronics. They have been joined recently by efforts funded by DARPA, whose decision to support this technology was due to the discovery of high-temperature superconducting materials in 1987. The Terahertz program in this area is but a subset of the total SDIO effort but is representative of the advances being made in this technology and its potential benefit for the DoD. Under this program research is being conducted at the U. of California at Berkeley and device development is ongoing at Westinghouse Science and Technology Laboratory in Pittsburgh and at Hypres, Inc. in Elmsford, NY.

The effort at Berkeley has been to develop A/D converters with the highest possible bandwidth. They have concentrated on flash-type architectures. In this scheme the signal is measured within a short aperture time at a bit parallel level (one comparator per bit) configuration or in a fully-parallel configuration (one comparator per digital level). The aperture time is quite severe for large bandwidth. For example, for four bits the aperture time is 20 ps at 1.0 GHz and 2 ps at 10 GHz. Two ps is quite pressing for Nb technology. Berkeley has designed a number of comparator circuits for both bit parallel and fully-parallel flash converters that approach the 10 GHz limit. They have also designed a shift register circuit which involves storage of superconducting flux quanta. Simulations have shown it capable of operating at clock speeds approaching 60 GHz.

Westinghouse brought a new balance to the Terahertz Program in digital superconducting circuits. Whereas Berkeley concentrated on conceiving new, ever more powerful A/C converter and shift register circuits, using computer models to simulate their performance and testing them, Westinghouse added a new and needed emphasis to the program: manufacture process control. This, of course, is an important aspect if this technology is to be brought to the stage of development that is necessary for inclusion in SDIO signal processing systems.

Westinghouse's first success was the demonstration of a 4-bit shift register which was clocked at 4 GHz. The power consumption was 0.45 mW. At the time, 1990, the was the world's fastest. Prior to this the top performer among superconducting shift registers was an 8-bit shift register made by Fujitsu in Japan. The Fujitsu circuit operated properly up to 2.3 GHz and the total power consumption was 1.8 mW. A GaAs 8-bit shift register has demonstrated at 3.2 GHz but the power consumption was 500 mW, 100 times greater than the Westinghouse shift register.

Hypres, in 1991, fabricated a superconducting 12-stage correlator chip that operates at 11.5 GHz and dissipates only 400µW. This is now perhaps the fastest in the world. The 16-stage correlator consists of two 16-bit shift registers with an XOR gate between each bit of both shift registers. The XOR outputs are added to produce a sum-of-products output. The goal is to

build a 4,096 stage correlator operating at 10 GHz.

A recent development offers the possibility of increasing the speed and decreasing the power consumption of superconducting circuits by yet another one to two orders of magnitude over that shown in Figure 1. This has been achieved in new logic circuits employing flux transfer devices. These circuits operate without ever or very seldom switching to the voltage state and thus consume less power. Flux transfer or so-call single-flux quantum (SFQ) circuits make use only of the superconducting properties of JJs such as the nonlinear inductance. Among SFQ circuits are the rapid single-flux quantum (RSFQ) logic family (which are short-pulse transmission devices) and the quantum-flux parametron and the parametric quantron (which are based on superconducting quantum interferometer devices - SQUIDS). The continuing effort at both Westinghouse and Hypres will employ SFQ techniques.

3. Superconductive Spread-Spectrum Communication System Development

The present status of the Terahertz Program allows the development for the first time of a high-data-rate communication system with a spreading bandwidth in the gigahertz range. This is due to the multi-gigahertz digital technology being developed by Westinghouse and Hypres and the time-integrating correlators from Lincoln Laboratory which have comparable bandwidth.

A gigabit communication system offers a number of benefits for the strategic mission of SDIO and for its new mission defined by the GPALS study. In the case of satellite cross-links where the danger of enemy jamming or eavesdropping is nil due to the frequency chosen (60, 120, 180 GHz), the ultra-high gigahertz data rate provides a ten-fold increase in information transfer over other systems now under development. Also, a broadcast mode of communication is possible employing multiple access modes afforded by spread-spectrum techniques such as Code-Division-Multiple-Access (CDMA). For up/down links at atmospheric frequencies (20, 44, 94, 140, or 220 GHz), CDMA or pseudorandom noise techniques allow for low-probability of intercept communications and continued robust operation in the face of jammers.

A superconducting modulator and demodulator development is planned. The specific goal is the demonstration of a 60 GHz CDMA communications system to provide multi-access communication capability between the constellation of satellites envisioned for the Brilliant Eyes missile defense system.

4. Summary and Acknowledgments

This paper describes the order of magnitude requirements for a submillimeter wave endo-KEW device for sensing and communications. It provides information on the current state of submillimeter wave technology in detectors, oscillators, mixers, and signal processors as well as technology goals and planned demonstrations for the future.

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